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A thermal active restrained shrinkage ring test to study the early age concrete behaviour of massive structures

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ABSTRACT

In massive concrete structures, cracking may occur during hardening, especially if autogenous and thermal strains are restrained. The concrete permeability due to this cracking may rise significantly and thus increase leakage (in tank, nuclear containment…) and reduce the durability.
The restrained shrinkage ring test is used to study the early age concrete behaviour (delayed strains evolution and cracking). This test shows, at 20 °C and without drying, for a concrete mix which is representative of a French nuclear power plant containment vessel (w/c ratio equal to 0.57), that the amplitude of autogenous shrinkage (about 40 μm/m for the studied concrete mix) is not high enough to cause cracking. Indeed, in this configuration, thermal shrinkage is not significant, whereas this is a major concern for massive structures.
Therefore, an active test has been developed to study cracking due to restrained thermal shrinkage. This test is an evolution of the classical restrained shrinkage ring test. It allows to take into account both autogenous and thermal shrinkages. Its principle is to create the thermal strain effects by increasing the temperature of the brass ring (by a fluid circulation) in order to expand it. With this test, the early age cracking due to restrained shrinkage, the influence of reinforcement and construction joints have been experimentally studied. It shows that, as expected, reinforcement leads to an increase of the number of cracks but a decrease of crack widths. Moreover, cracking occurs preferentially at the construction joint.

1. Introduction

At early age in massive concrete structures, cracking may occur during hardening. Indeed, hydration is an exothermic chemical reaction (temperature in concrete may overcome 60 °C [1–3]). Therefore, if autogenous and thermal strains are restrained (self restraint, construction joints), compressive stresses and then tensile stresses rise, which may reach the concrete strength and induce cracking in a real structure. For instance, Ithuralde [1] observed several crossing cracks (opening up to 0.5 mm) in a 1.2 m width concrete wall (representative of French nuclear power plant containment), cast on a concrete slab. For structures like tanks or nuclear containment vessels, this cracking may significantly increase concrete permeability and reduce tightness. For other massive structures (bridges, tunnels…), the serviceability may be reduced due to the penetration of aggressive species (such as carbon dioxide, sulfate and chloride ions).

The restrained shrinkage ring test is used to determine the concrete behaviour (creep strain and cracking) due to autogenous and drying shrinkages. In this study, a concrete mix, which is representative of a French nuclear power plant containment vessel, is tested. This test shows that, at 20 °C with this concrete and without drying (for nuclear power plant containment the formwork remains during about 2 weeks after casting, which prevents drying and thus subsequent cracking due to drying shrinkage at early age) the amplitude of autogenous shrinkage is not sufficient to cause cracking. Indeed, in this configuration (classical restrained shrinkage ring test), thermal shrinkage does not occur whereas in massive structures thermal strains restraint (due to internal restraint, i.e. temperature gradients or due to construction joints) is the main phenomena involved in cracking [4,5]). Therefore, a device, which is an evolution of the classical restrained shrinkage ring test (devoted to be representative of a massive structure), has been developed to study the cracking due to restrained thermal shrinkage in laboratory conditions. Effectively, to the authors' knowledge, only few experimental devices exist in literature to study cracking due to the restraint of thermal shrinkage [6,7] and requires a complex load system or are limited to mortar samples.

Cracking highly depends on creep (essentially basic and thermal creep in massive structures). However, the question whether creep strains are the same in compression (such tests are “classical”) and

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Table 1
Concrete mix.

Portland composite cement (6% of limestone powder)	kg/m^3	350
Sand (0–5 mm)	kg/m^3	772
g (5–12.5 mm)	kg/m^3	316
G (12.5–20 mm)	kg/m^3	784
Water	L/m^3	201
Superplasticizer	L/m^3	1.225

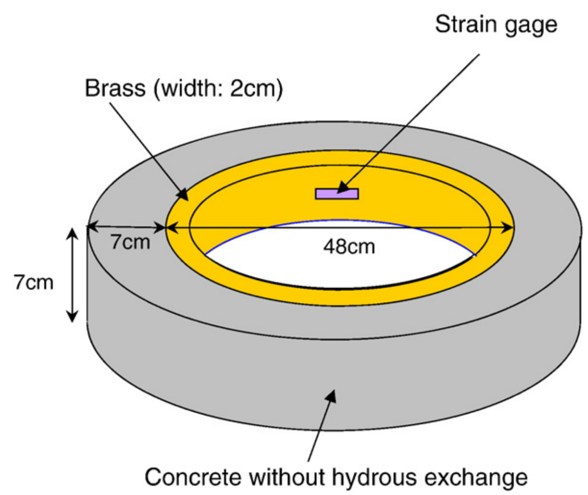

Fig. 1. "Classical" ring test geometry.

in tension (difficult to perform) is not fully resolved [4,8]. The device developed in this study allows the identification of tensile creep strains as well. In this paper, after a presentation of the active device, the early age cracking due to restrained shrinkage will be experimentally studied. Then, the influence of reinforcement, construction joints and temperature rate evolution will be highlighted.

2. Active shrinkage ring test

The test used in this study is an evolution of the restrained shrinkage ring test which allows to take into account both autogenous and thermal shrinkages. After a review of the "classical" restrained shrinkage test and the presentation of the results obtained with one of them, this part will present the proposed evolution.

2.1. "Classical" restrained shrinkage ring test

Many devices have been developed to study the behaviour of concrete submitted to restrained shrinkage. We can divide them in three main types:

- Shrinkage is restrained in one dimension (see [6,7,9–12]).
- Shrinkage is restrained in two dimensions (see [13–15]).
- Ring test (see [16–19]).

The most common test is certainly the ring test. The "classical" ring test was initially designed to observe the cracking of a concrete ring specimen cast around a rigid core (usually made of steel e.g. by [16]): only the cracking age can be measured and the stresses generated by restrained shrinkage could not be deduced. Then, Paillère [17] and Swamy [18] optimized the ring dimension and added instrumentation to measure strains on the steel ring. Strain gages were placed on the steel ring to deduce stresses in concrete ring [19]. The configuration of this test offers several advantages and particularly the fact that stresses are self generated by restrained shrinkage and specimen geometry. Finally, a fracture mechanics approach was used to highlight the influence of the ring geometry and especially the width of the ring on the cracking [20].

As a classical restrained ring device was available in our laboratory, a concrete mix representative of a French nuclear power plant containment vessel has been tested (Table 1). The used cement is a Portland composite cement (6% of limestone powder). Fig. 1 displays the brass (brass is preferred to steel to limit chemical reaction between the metallic ring and the concrete) and concrete ring geometry (concrete ring section: 7 cm × 7 cm). Concrete is protected from hydrous exchange and strains measurements are performed by gages placed on the internal radius of the brass ring.

2.2. "Classical" restrained shrinkage ring test results

Fig. 2 shows the temperature evolution measured during the classical test. A decrease of the concrete temperature is observed at the beginning, since the temperature of the raw materials is higher than the room temperature. Then an increase (due to hydration exothermy) of 2.5 °C, followed by a cooling phase of concrete, is measured. For the same mix, Ithurralde [1] measured a variation of 40 °C in a 1.2 m width wall. The evolution of the orthoradial brass strains is given in Fig. 3. At the beginning, this strains evolution is due to thermal strain. Next, the evolution is due to restrained concrete autogenous shrinkage. Fig. 3 also displays the orthoradial stresses evolution in both materials and the evolution of concrete tensile

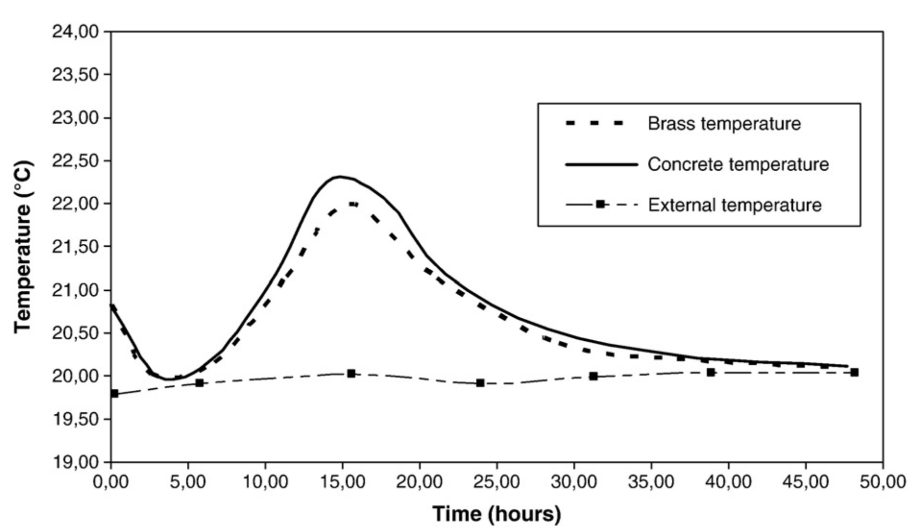

Fig. 2. Temperature evolution during the "classical" restrained ring test.

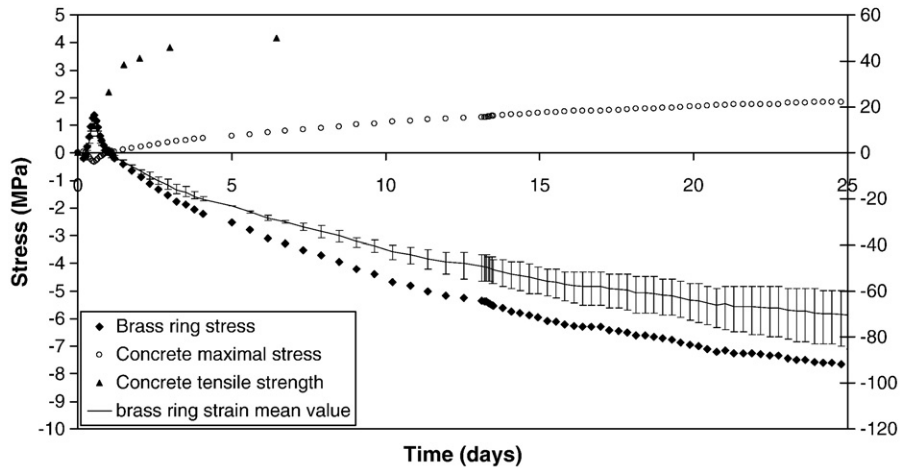

Fig. 3. Stresses evolution during the "classical" restrained ring test.

strength (measured by a splitting test). The orthoradial stresses in the brass and in the concrete ring are calculated from the orthoradial brass strains (measured by strains gages placed on the inner radius of the brass ring) with Eq. (1) given by Hossein and Weiss [21]:

$$\sigma_{Actual-\max} = -\varepsilon_{brass}(t) \cdot E_b \cdot \frac{R_{OB}^2 + R_{OC}^2}{R_{OC}^2 - R_{OB}^2} \cdot \frac{R_{OB}^2 - R_{IB}^2}{2R_{OB}^2} \quad \text{I}$$

where $\sigma_{Actual-max}$ is the maximal stress applied in concrete, ε_{brass} is the brass strain on the inner radius of the brass ring, E_b is the brass Young modulus, R_{OB} is the outer brass ring radius (=24 cm), R_{OC} is the outer concrete ring radius (=31 cm), R_{IB} is the inner brass ring radius (=22 cm).

No macroscopic crack in the concrete ring was experimentally observed. This is confirmed in the strains measurement (no strain gap) and in Eq. (1): the stresses generated by the restrained autogenous shrinkage do not exceed the concrete tensile strength (see Fig. 3). In fact, in this test, on the one hand, autogenous shrinkage of the studied concrete is low (about 40 µm/m) and on the other hand, the specimen is not massive enough to present the same thermal evolution as in a massive structure. Consequently, the effect of thermal shrinkage is negligible in this test (although its role is crucial in massive structures). This highlights the need to develop an adapted device for massive concrete structures (even if autogenous shrinkage is sufficient to create cracking in lower w/c ratio), which is presented below.

2.3. An active restrained shrinkage ring test

Original active ring tests have been developed: Haouas [22] used an internal pressure and Gagné [23] and Messan [24] used an expanded core to create tensile stress state. Nevertheless, these devices used mortar and could not be easily adapted to concrete because the pressure or the applied load would grow significantly. Moreover, thermal strains, which are a major concern for massive structures, as shown previously, do not develop in these devices. Thus, a new kind of active ring test has been developed. Recently, a thermally controlled dual ring was developed by Schlitter et al. [7] to study both thermal and autogenous expansions and shrinkage of mortar.

The ring test proposed in this study aims at predicting the behaviour and the cracking of concrete at early age of massive structures (like a nuclear power plant containment) and is also a thermally controlled device. Nevertheless, whereas the dual ring of Schlitter et al. [7] tends to create constant restraining boundary, the proposed devise causes moving boundary. Its principle is to create the thermal strain effects by increasing the temperature of the brass ring in order to expand it and to reproduce a stress rate similar to the one of a real massive structure. In this case, the expansion of the ring is restrained by the external concrete

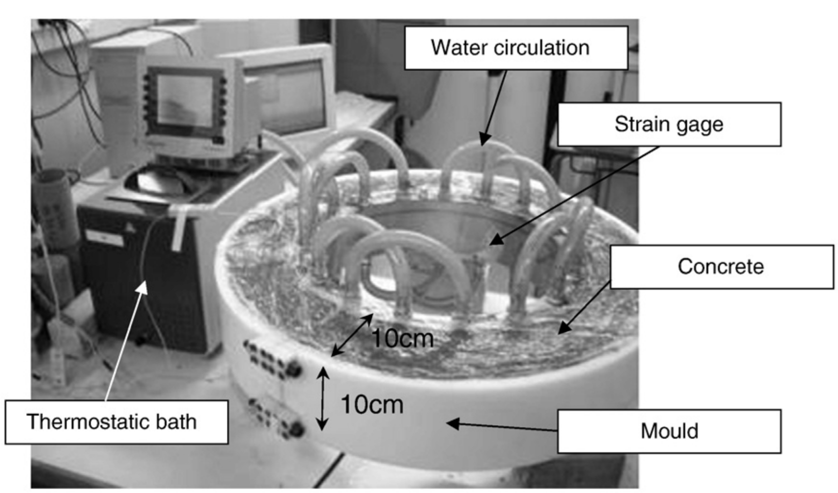

Fig. 4. Thermal active ring test.

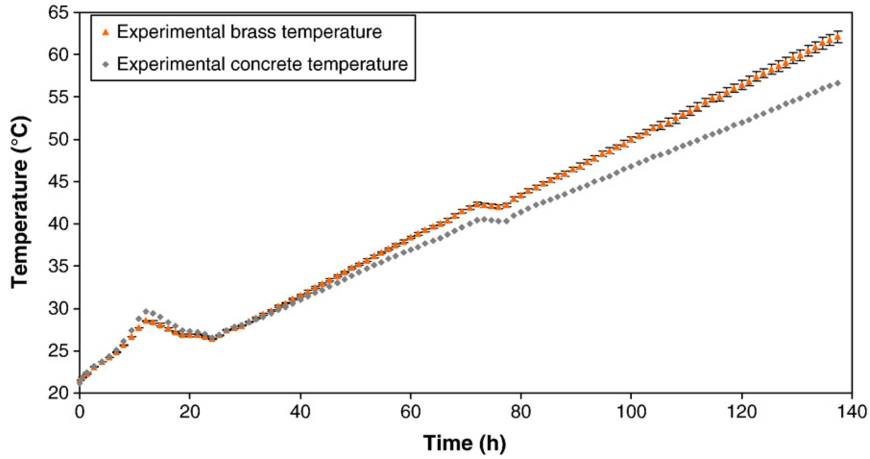

Fig. 5. Active ring test temperature evolution.

layer (the thermal dilatation coefficient of the brass is about 3 times higher than the concrete one). This induces compressive stresses in the ring and therefore tensile stresses in concrete. The temperature evolution of the brass ring is punctually regulated by water circulation into the ring, created by a thermostatic bath (Fig. 4). The brass ring strains are measured by 3 strains gages placed at 120° and two temperature probes are placed in an opposite way on a same diameter. This idea was already proposed with a Plexiglas core, which has a thermal dilatation coefficient 10 times higher than the concrete one [25]. Nevertheless, with this device, the strains measurements were not directly available which limits the results exploitation.

The objectives are to reproduce a similar stress history than the one which occurs in a "real" massive wall [1,4] and to measure strain directly on the ring (it allows to detect cracking and to identify creep, see afterwards). In fact, in this test, the temperature increase of the brass ring creates tensile stresses in the concrete ring which correspond to a temperature decrease in reality. The temperature brass increase rate is calculated thanks to finite element simulations or experimental temperature data [1]. The temperature decrease on the massive wall core (between 24 and 124 h) can be correctly approximated with a linear decrease of 0.35 °C/h (which depends on the concrete mix, thickness, boundary conditions…). Thus, this temperature increase rate will be applied to the brass ring.

The specimen dimensions in the active ring test have been chosen to obtain a concrete ring section of 10 cm × 10 cm. Indeed, the aggregate maximal size of our mix is equal to about 20 mm, and the section of the classical ring used in Section 2.1 of this article (7 cm × 7 cm) is not large enough to obtain a representative concrete section. Moreover, reinforced concrete is also studied and a smaller section cannot guarantee a cover representative of a real structure. The dimensions of the brass ring (the internal radius and the ring width) have been calculated to obtain measurable strains in the ring (strains gages accuracy is about 5 μm/m) but also to stay in a reasonable range of weight: 19 cm for the internal radius and 3 cm for the ring width. The presence of holes in the brass (for water circulation) induces a global stiffness decrease of 9% but only a variation of about 4% on the orthoradial strains measurement with respect to the mean value (calculated by finite elements) because the length of the gage and their location tend to smooth the local variation (about 11%). Since drying is 1000 to 10000 times slower than heat transfer [26], and because the formwork is removed 15 days after casting (in nuclear power plants), massive structures at early age are almost in endogenous conditions (except for the external concrete skin). Therefore, tests are performed with no hydrous exchange with the environment. To prevent this exchange, the concrete ring is covered with an adhesive aluminium layer [27] (the weight loss is less than 0.1% after 7 days).

It should be noticed that this device is well adapted to describe cracking during concrete lift, but cannot retrieve thermal stresses due

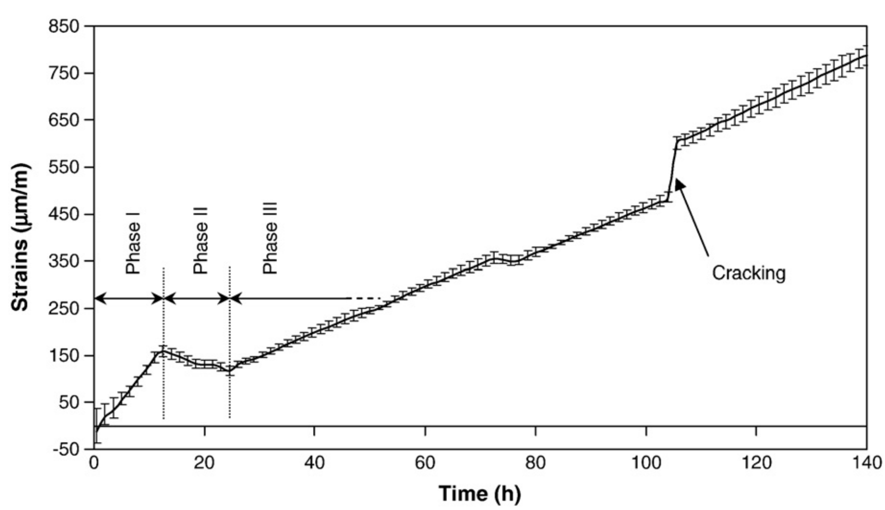

Fig. 6. Evolution of orthoradial strain in the brass (mean, maximal and minimal values).

Table 2
Experimental cracking results.

Temperature rate (°C/h)	Construction joint	Reinforcement	Cracking age (h)	ΔT at cracking (°C)	Crack width (μm)
0.17			135	19.8	600
0.35			95	21.2	650
0.35		X	109.5	27.7	100 50–100 100
0.35	X		66.5	13.9	550
0.7			60	21.9	650

to self restraint (temperature gradient inside the thickness). However, numerical simulations show that, for the studied concrete, thermal stresses due to self restraint do not lead to cracking [4].

3. Active restrained shrinkage ring test experimental results

3.1. Analysis of the experimental results

The brass ring and concrete temperatures are measured by thermocouples (Fig. 5) (type K are placed on the internal radius of the brass ring and on the middle of the concrete section) and the orthoradial brass ring strains are measured by three strain gages on the internal radius of the ring (Fig. 6). The brass strains are corrected to take into account the strain gage thermal dilatation. All experimental results are summarized in Table 2.

Although the temperature is punctually imposed by the fluid circulation in this test, Fig. 5 shows that a quite homogeneous temperature is obtained in the ring. At the beginning of the test (up to 10 h), the temperature increase is due to the (exothermic) hydration reaction (Phase I). It induces an increase of brass strain (Fig. 6). Next, a decrease of temperature is observed (the heat losses are greater than the hydration heat release). This decrease corresponds to phase II. An associated thermal shrinkage is observed. Then (after 24 h), the temperature rise is imposed by the thermostatic bath with a rate of 0.35 °C/h (phase III). During the test, a constant temperature is imposed (42.8 °C) to verify that the device does not have too much thermal inertia. During this third phase, the ring strain becomes a combination of the thermal dilatations of the brass and concrete rings. In all phases, autogenous shrinkage occurs. However, it has only a slight influence, since its amplitude is about 40 μm/m for the studied concrete mix.

The first result is that an experimental crack (Fig. 7) is effectively obtained in this test which corresponds to a gap in the strain evolution (Fig. 6). Only one crack occurs for a brass ring temperature value of 51.5 °C (experimental crack width was about 650 μm: see Fig. 7). Indeed, after cracking, stresses are relaxed by the debonding of the concrete ring from the brass ring. Besides, the crack crosses the entire concrete specimen section and furthermore, continues through the concrete aggregates. Moreover, the brass ring orthoradial stresses seem to be uniform (along the circumference) because the three strain gages measurements are quite similar before cracking.

In a real massive structure, concrete is reinforced by reinforcement bars. Moreover, massive elements cannot be cast in one concrete pour and construction joints are needed. The effects of the reinforcement and the construction joints are not similar because the reinforcement bars tend to distribute the cracks and to limit the crack opening whereas the construction joints tend to decrease the massive structure homogeneity and to create weak areas (splitting tests show a tensile strength decrease of about 25% at the construction joints). Therefore, the influence of both reinforcement and construction joints have been studied separately in addition to the temperature rate effect.

3.2. Reinforcement bars effect

To study the effect of reinforcement on cracking, two 8 mm diameter reinforcement bars have been placed in the middle of the concrete section. In order to guarantee the stress continuity in the bars and to avoid any recovering length, reinforcement bars have been welded to obtain steel rings (see Fig. 8).

With reinforcement, more than one crack is obtained. In Fig. 9, four cracks can be observed. Among these, two are crossing cracks, whereas the other two do not seem to be (Fig. 9).

The obtained mechanical results are presented in Fig. 10. It represents the brass strains evolution. In this graph, strains have been reinitialized at the beginning of the temperature increase (the time when temperature is imposed by the hot water circulation). It shows

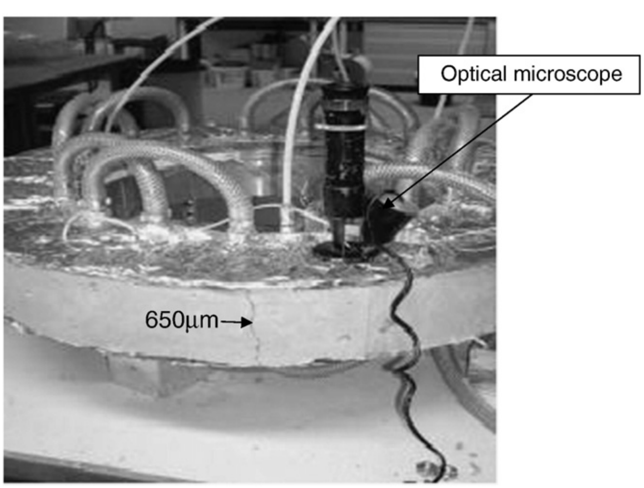

Fig. 7. Experimental crack picture.

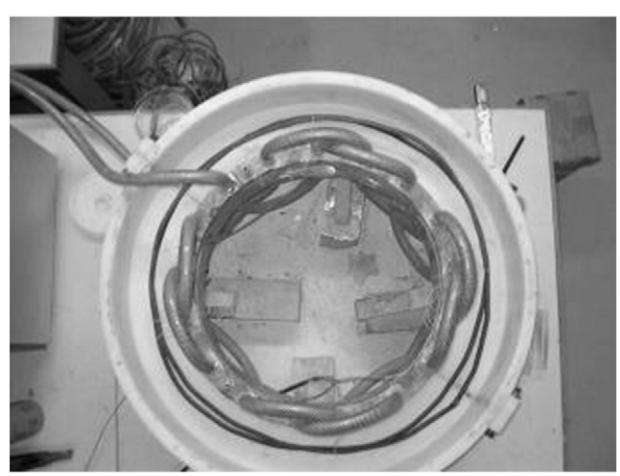

Fig. 8. Ring reinforcement.

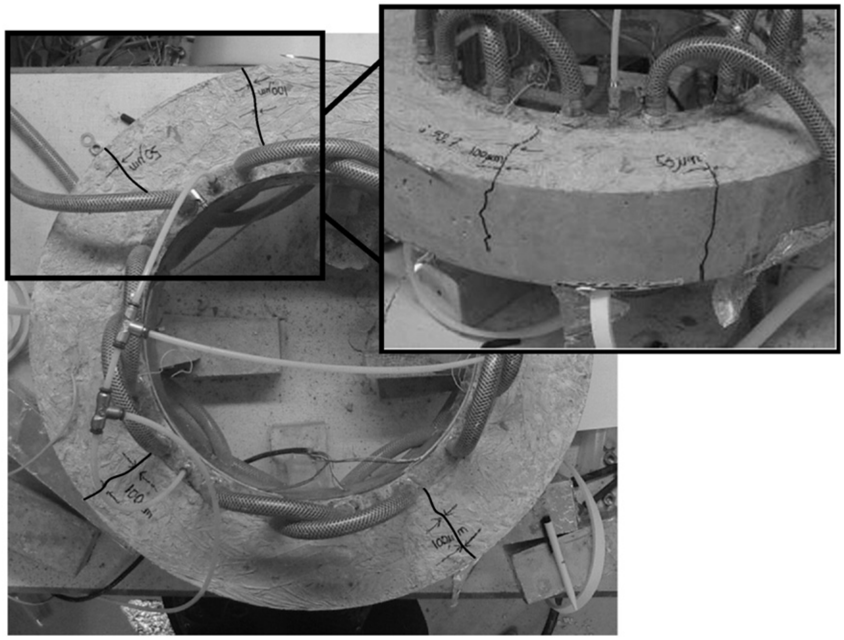

Fig. 9. Cracks location in the reinforced concrete ring at the end of the test.

that the concrete crack appears later than for the concrete without bars. Effectively, the crack is obtained for a temperature increase of 27.7 °C (the reference corresponds to the time when the temperature is imposed by the circulation of hot water) whereas the temperature increase at the time of cracking for the concrete without bars is equal to about 21 °C. Moreover the strain gap on the strain evolution is lower compared to the gap obtained with a ring without reinforcement bars. This indicates that the crack opening is reduced due to the presence of reinforcement bars which can also be experimentally observed in Fig. 9 (the maximum cracks opening is equal to about 100 μm whereas the crack opening in the test without bars was equal to about 650 μm).

3.3. Construction joints effect

In order to study the influence of the construction joints on the early age behaviour of massive structures, a concrete ring has been cast in two parts. The first part is made up of two quarters of the ring placed on the same diameter and the second part is composed by the two other parts of the ring (Fig. 11). The second part is cast two weeks later than the first one (which is representative of a nuclear power plant construction). Thus, a complete ring with four construction joints is obtained. Note that in this test, no reinforcement has been used.

To obtain a roughness of the surface representative of the surface state of massive structure construction joints, the surfaces between the two parts of the ring have been mechanically scraped. The results of the test are presented in Fig. 12.

On this graph, the strains have also been reinitialized at the beginning of the temperature increase. As expected, it shows that concrete cracking is obtained earlier than for concrete without construction joints (for a temperature increase of 13.9 °C instead of about 21 °C). Indeed, the crack appears in the construction joint, where the tensile strength is lower than in the bulk concrete (it is

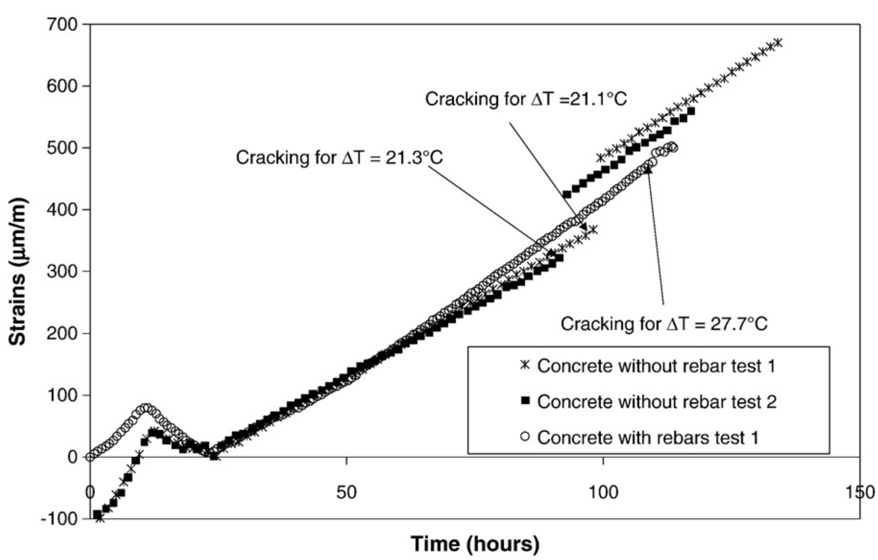

Fig. 10. Evolution of orthoradial strain in the brass: effect of reinforcement.

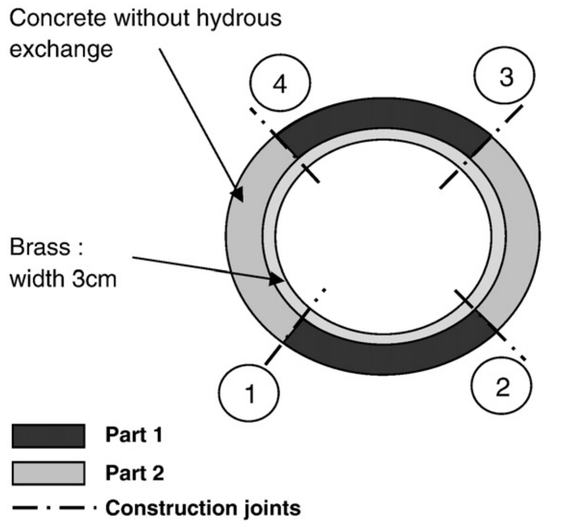

Fig. 11. Scheme of the cast partition for the ring with construction joints.

recalled that splitting tests show a tensile strength decrease of about 25%). It is interesting but fortuitous to note that the benefit from the reinforcement bars addition on the cracking time (about 7 °C) is approximately the same as the loss due to the construction joints.

In this test, only one crack at one construction joint is obtained and its width is equal to about 550 μm. This crack opening is slightly lower than for the concrete without reinforcement bar and without construction joint, given the fact that the cracking temperatures are lower.

This study shows that the effects of the construction joints are very important and harmful for the mechanical strength of concrete, especially in tension. This is why the massive element modeling has to take into account the construction joints as well as the construction stages. Otherwise, long term performance could be overestimated.

3.4. Influence of the temperature increase rate

With this active device which allows to create a macroscopic tensile crack, the influence of the temperature increase on the cracking time and on the strains evolution has also been studied. Indeed, the evolution of temperature in concrete structures depends on several parameters (including the temperature of the raw materials, external temperature, wind, sunshine, cement type, formwork type, formwork removal time,…) and so, our test temperature increase needs to be modified. The temperature rates are multiplied or divided by two in comparison to the initial temperature rate (0.35 °C/h). The results are presented in Fig. 13. For each temperature rate increase, at least 2 tests or more were performed but only one is represented in Fig. 13. In fact, for a same temperature increase, cracking times are very close (±1 h for the fastest temperature increase, ±2 h for the slowest one). Let us mention that this observed variability on cracking time is partly due to the variability of external temperature (25±3 °C) so a representation with an error (or variability) bar is not relevant.

A slight increase of the cracking temperature (which is calculated with respect to the temperature at the beginning of the active test) is obtained with the temperature rate increase. This result seems to be paradoxical because the tensile strength is smaller. Nevertheless it is difficult to conclude regarding the low cracking temperature difference. Moreover, a slight strains decrease is noticed as the temperature rate increases. Again, the conclusions are not readily apparent. In fact, in this test, there is a competition between the stresses rise (which is not the same due the concrete stiffness depending on hydration degree and thus, on temperature), the evolution of concrete tensile strength (evolving differently from stiffness) and basic and transient thermal creep. Moreover, at early age, the concrete creep rate is important. With a uniaxial-restrained shrinkage test, the creep effect can be determined [28] but in the case of a steel ring, the analysis is more complicated. This highlights the need to perform numerical simulations which will be presented in another paper.

4. Conclusion

In this study, an active ring test has been developed to investigate the early age behaviour and cracking of massive structures. Involving temperature and hydration effects, this modification of the classical restrained ring test is essential because this one did not take into account the thermal strains. Thus, the classical test is not able to reproduce a realistic stress state as it can occur in massive structures.

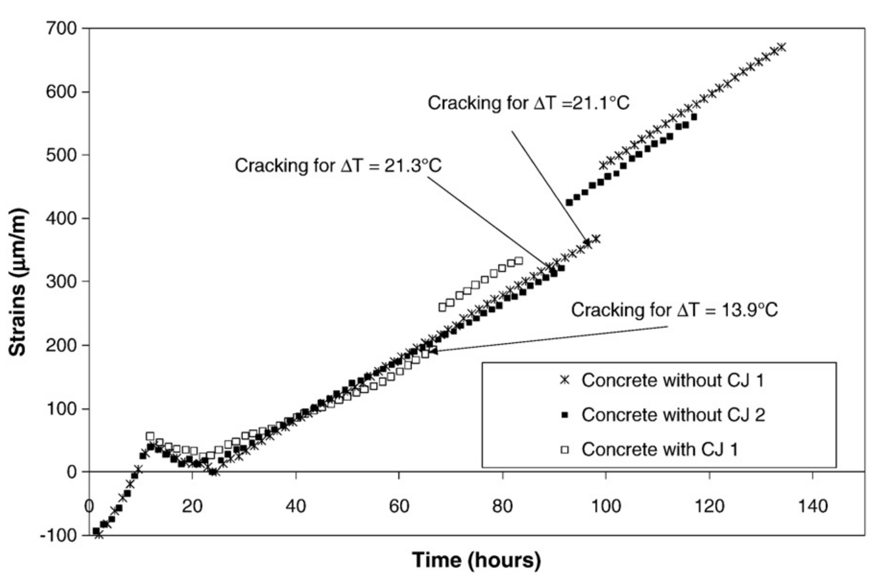

Fig. 12. Evolution of orthoradial strain in the brass: effect of CJ (CJ = construction joints).

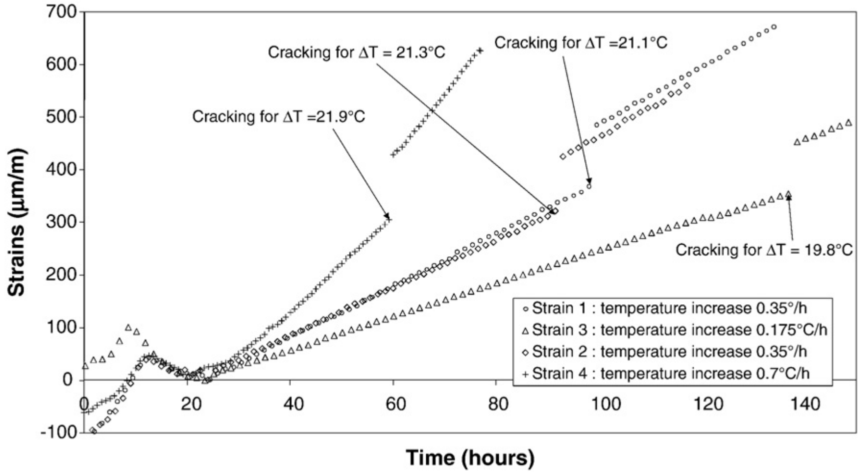

Fig. 13. Evolution of orthoradial strain in the brass: effect of the temperature increase rate.

The active device is an evolution of the restrained shrinkage ring test. The thermal strain restraint is created by an expansion of the internal brass ring to reproduce approximately the stress state of a real massive structure. The expansion of the ring is obtained by the circulation of hot water into the brass ring.

Moreover, a study on the effect of steel bars reinforcement and construction joint was performed with this device. The results showed that the effects of reinforcement bars are multiple (cracking is delayed, cracks openings are reduced and cracks are distributed). They also corroborate the fact that construction joints considerably reduce the strength of the concrete element and highlight the fact that they must be taken into account in the modeling of massive structures.

Nevertheless, many phenomena simultaneously occur in this test (hydration, shrinkage, creep…). In order to perform a relevant analysis of this test (especially identification of creep in tension), complementary tests and numerical simulations need to be performed and are currently undertaken.

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